

A Fast Technology Infusion Model for Aerospace Organizations

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Abstract—A multi-year, Fast Technology Infusion initiative is presented which seeks to develop a model for aerospace organizations to improve the cost-effectiveness by which they mature new, in-house developed software and hardware technologies for space mission use. The first year task under the umbrella of this initiative will provide the framework to demonstrate and document the fast infusion process. The viability of this approach will be demonstrated on two technologies developed in prior years with internal Jet Propulsion Laboratory (JPL) funding. One hardware technology and one software technology were selected for maturation within one calendar year or less. The overall objective is to achieve cost and time savings in the qualification of technologies for space use. At the end of the recommended three-year effort, we will have demonstrated for six or more in-house developed technologies a clear path to insertion using a documented process that permits adaptation to a broad range of hardware and software projects.^{1,2}

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1. INTRODUCTION

This paper describes a multi-year initiative which will create a pathway for new technology infusion in both software and in hardware. The overall objective is not to space-qualify the technologies for one specific space mission, but find the major obstacles to insertion which are deemed to be make or break hurdles for a large class of relevant missions. A general technology infusion flow is outlined in the next section and will be refined as part of the development effort. The JPL “Technology Infusion Maturity Assessment” (TIMA) process will be used to clarify the definition of the mission requirements, identify and address early difficulties resulting from mission architecture decisions, and gauge capabilities of competing technologies. At the end of the three-year effort, we will have demonstrated for at least six in-house developed technologies a clear path to insertion using a documented process that permits adaptation to a broad range of hardware and software projects.

The objective of the software subtask is to verify the effectiveness and suitability of a form of automatic code generation. This autocoding will take a high-level state-chart description of a software system and automatically generate code to implement that system. The subtask will demonstrate state-chart design and automatic code generation for the Proximity-1 communications protocol used by JPL’s Mars Reconnaissance Orbiter (MRO) and Mars Science Laboratory (MSL) for their Electra Telecom Subsystems. This demonstration will show reduction of development costs, increased reliability, and facilitation of consistent changes to any mission’s payload flight software.

The objective of the hardware subtask is to verify the effectiveness of using “radiation tolerance by design” mitigation of single-event upsets in an existing in-house-

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² IEEEAC paper #1607, Version 3, Updated December 11,, 2006

developed, high performance single board computer (SBC). The innovative hardware qualification will lead to the unambiguous demonstration of a single event upset (SEU) mitigation technique for the entire board circuitry through full system radiation exposure.

In the context of this paper, technology infusion means the pathway by which technologies, previously unused by space flight programs, move from their current status onto space flight missions. The technology can be several generations old, state-of-the-art, or anything that is deemed useful to the accomplishment of NASA space missions. The motivation for focusing on technology infusion is that there appears to be a development “gap” between laboratory bench research and development (R&D) and flight-ready systems. Further, it also appears that proportionally little funding is available to assist technologies in bridging the “gap.” The program described in this paper is an attempt to begin to address both of these issues. Some additional strategies and observations regarding the development gap may be found in Shapiro [1].

TRL at NASA

The National Aeronautics and Space Administration (NASA) has a system for rating where in the development cycle any particular technology resides. This system, called the Technology Readiness Level (TRL), can be found in Mankins [2]. The levels are listed in Table I, and can be seen to range from inception of a concept to flight-proven. “A modified interpretation of these aimed solely at information technologies” is presented in Mackey et al. [3]. The objective of this program will be to expedite the move of technologies from TRL3 to TRL6. This is the so-called technology gap mentioned above.

Traditionally, new technologies that are mission-critical are funded by the programs that need them and new technologies that are not mission-critical are rejected because the missions do not want to accept additional risks. One of the things that this initiative is designed to do is to help transition items that may not be listed as mission-critical into flight programs by reducing the perceived risk to a level that the missions will accept.

Table I. Definitions of Technology Readiness Levels for NASA [2]

TRL Level	Description
9	Actual system “flight proven” through successful mission operations
8	Actual system completed and “flight qualified” through test and demonstrated on the ground or in space
7	System prototype demonstrated in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment on the ground or in space
5	Component and/or breadboard validated in a relevant environment
4	Component and/or breadboard validated in a laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept achieved in a laboratory environment
2	Technology concept and/or application formulated
1	Basic principles observed and reported

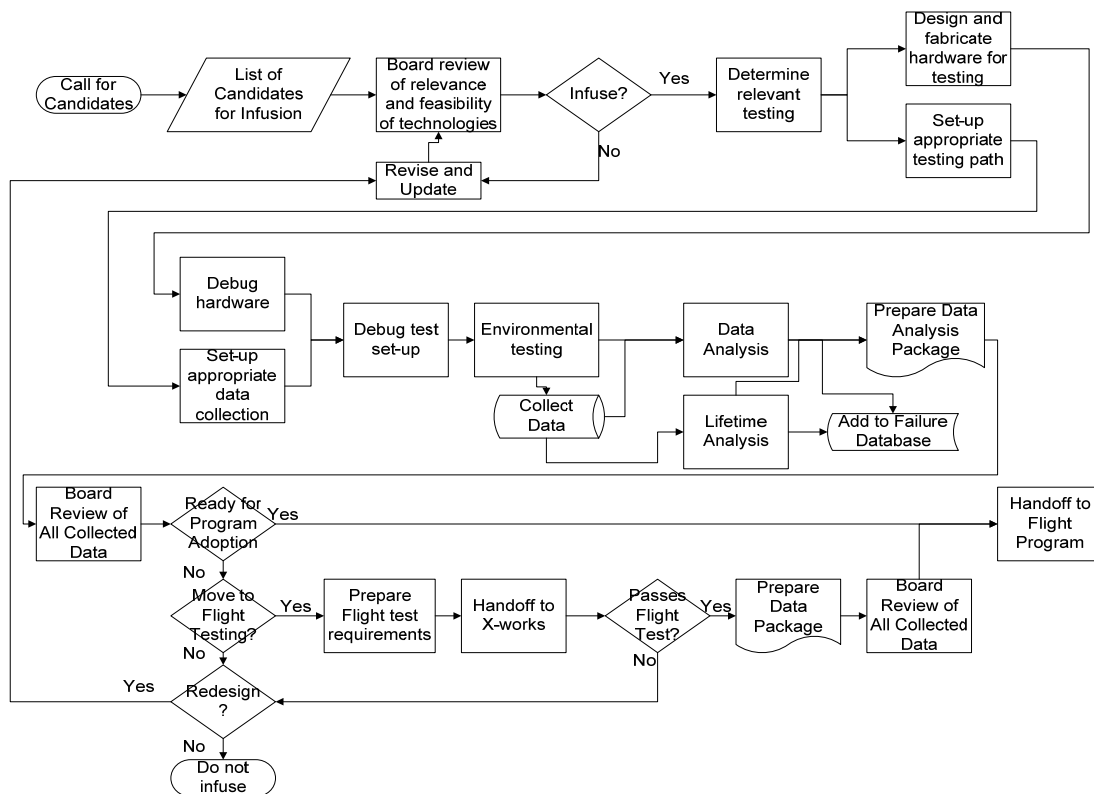


Figure 1. Proposed technology infusion flow chart.

2. OVERALL STRATEGY

JPL has a wide variety of technology demonstration programs such as NASA's New Millennium Program, NMP Earth Science Technology Office's AISR and AIST, the "Airborne & Ground demo of Mid TRL Instruments & Technologies" Initiative, Instrument Incubator programs, and JPL's Mars Focused Technology program. These programs are used to verify the operational viability of new technologies in an applicable space environment. However, with the exception of NMP and the Mars Focused Technology, they are not directed at TRL 4-6 technologies and with the exception of NMP assume that the environmental requirements will not pose a significant risk. Any technology where meeting the mission requirements are unknown or even considered questionable, too costly, or too lengthy will not find a place in the existing framework of demonstration programs. This initiative will uniquely concentrate on programs that have been developed at JPL but are considered too immature or high-risk for a mission to adopt without further validation. Using a unique infusion process, this task will mature two JPL technologies (one hardware and one software) from TRL 4 to 6 and demonstrate that a qualification for TRL 6 is going to be very likely by eliminating the major obstacles for full space qualification. A generalized fast maturation process will be the ultimate goal of the study.

As part of this effort the technology infusion flow shown in Figure 1 will be refined, leading to a process that identifies the highest insertion risk factors for a project and develops a physics based approach to mitigating those risks

The overall objective is to achieve cost and time savings in the qualification of technologies. The keys to doing so are:

1. Use of first-principles knowledge to triage qualification areas; for hardware technologies, a physics based approach will be followed, and for software technologies, a focus on fundamental concerns of both the development process itself and the operations-time needs. The advantages of this are:
 - Ranking of the infusion impediments
 - Identification and selection of the most appropriate treatment of those impediments – in some cases traditional qualification (or the pertinent subset) will be called for, in other cases the impediments may be accommodated with the mission design (e.g., rather than qualify to very low levels of induced vibration, plan for use of vibration insulation).
2. Matching of technologies to the driving needs and constraints of classes of space missions. The

advantages of a focus on mission classes rather than on just one specific mission are:

- Ensure the technology is qualified for as broad as possible utilization, thus maximizing its potential for infusion into mission use.
 - Establishment of a reusable set of mission profiles, so that further technologies can take this as a starting point for estimating their own infusion.
3. Initial identification of the most critical impediments to infusion, with the qualification steps to follow focused first on those impediments. The advantages of this are:
- Certainty (or evidence of unsuitability) in the technology is gained as quickly as possible, allowing missions to plan accordingly
 - Early discovery of areas most likely to be in need of rework, thus sparing the effort of re-performing other qualification steps subsequent to that rework.

At the end of the recommended three-year effort, we will have demonstrated six or more in-house developed technologies with a clear path to insertion and a documented process that permits adaptation to a broad range of hardware and software projects.

Related Work

Many obstacles impede the infusion of software engineering research results into the development community. Practitioners cannot readily identify the emerging techniques that may benefit them and cannot afford to risk time and effort evaluating and trying out new techniques while there is uncertainty as to whether they will work for them. These were recognized as problems for infusing software engineering technologies into NASA use [4]. In response, a “broker” based approach was established to foster the infusion of particularly promising technologies (ones that would require little or no additional development to be applied) [5]. By way of contrast, this initiative focuses on technologies for which a significant effort is still needed to adequately demonstrate their viability and suitability for a given purpose.

3. INFRASTRUCTURE DEVELOPMENT

The Two Sigma Environment

One of the difficulties encountered for spaceflight qualification methods is that there are no standard space environments. Missions to Mars are substantially different from earth orbiting or lunar missions. Additionally, Mars orbiting missions are significantly different from Mars

roving missions. Although the environments are substantially different, a number of factors are very similar. Typically, launch vibration and shock loads are similar. Often general reliability requirements are also related. In an attempt to focus on the similarities between missions, a concept was developed by Cornford and Gibbel [6] of a two sigma environment or one in which captures about 95% of the space qualification requirements (two standard deviations above and below an “average” environment). This two sigma strategy would allow a particular technology to be evaluated by the majority of common spaceflight test methods removing the bulk of the risk for any individual mission. The individual missions would then only need to perform a small number of tests that pertain to that mission’s specific environment.

If used extensively, this strategy could save substantial dollars and time by having the testing common to many missions already performed, saving the cost of each mission having to perform a complete battery of tests.

The Technology Infusion Maturity Assessment (TIMA) Process

The Fast Technology Infusion initiative will exploit a previously-developed JPL process to assist in technology infusion. In this section we summarize that process, and describe how we are now using it to help speed up the infusion process.

This process, called “Technology Infusion Maturity Assessment”, was constructed to address several of the recurring obstacles to successful technology infusion, specifically: (1) customer (mission) requirements for using the technology were either miscommunicated, misunderstood, or under-defined, (2) the technology was deemed non-flightworthy in its current state of development (i.e., the technology was subsequently rejected because of some unforeseen engineering issues), and (3) other nearly-equivalent commercially-available technologies could possibly replace NASA-developed technologies. The net result of these obstacles was that disappointingly few of the promising technologies emerging from the research laboratory stage as proof-of-concepts mature to actual use.

The TIMA process was developed to address these challenges. It takes the form of a series of facilitated group sessions in which participants provide information pertinent to the infusion of the specific technology being considered. Custom-developed software supports the process, enabling on-the-fly capture of information, supporting the combination of the gathered information, providing reasoning over that combination, and offering visualizations to help convey status of the information and its combination to the participants. An in-depth discussion of the TIMA process and its software support is described by Feather et al. [7]. For the purposes of this paper, we briefly summarize

the main steps of information gathering in the TIMA process:

Identify the customer requirements that the technology needs to meet before designers and managers will have adequate confidence to infuse the technology into a flight project. Assess the *relative importance* of those requirements by ascribing numerical weights to them in proportion to their estimated importance.

Determine the potential, relevant failure modes of the technology. Assess how the *impact* of each failure mode can affect the requirements by ascribing a numerical proportion of requirement lost were that failure mode to occur.

Identify all the options available to prevent, diminish, or detect and correct (before actual use) failure modes. TIMA refers to the range of such options as PACTs, shorthand for **P**reventative measures, **A**nalysis, process **C**ontrols, and **T**ests (PACTs). Assess the *effectiveness* of each PACT against each failure mode, by ascribing a numerical proportion of the reduction in the failure mode's likelihood or impact (depending on the type of PACT) application of the PACT will realize. Also, estimate the *costs* (dollars, schedule, etc.) of each PACT as part of an engineering model fabrication and test program for the technology in question.

Once this information has been gathered, it then becomes possible to conduct decision making based on the combination of that information:

Determine the optimal Cost/Benefit funding recommendations that will improve technology infusion success.

Be prepared to discard problematic requirements (those significantly impacted by failure modes that would be extremely expensive to prevent/ diminish/ detect and correct). Note that doing so will likely reduce the range of applicability of the technology.

For the chosen budget, select a set of PACTs that (near) optimally achieve a reduction of risk (from the identified failure modes) while remaining within budget.

Fast infusion will make use of the TIMA process adapted in the following ways to address the goal of cost and time savings in the qualification of technologies.

Definition of the two-sigma environment will gather a reusable set of information that will help populate the TIMA process. For example, think of characterizing the typical range of shock and vibration that a piece of hardware must survive during launch. This information will

pre-populate the TIMA process, providing "requirements" information (e.g., vibration levels that must be survived), typical "failure modes" (e.g., the forms of damage caused by vibration), and typical "PACTs" [solution options] (e.g., vibration isolation designs; qualification tests sufficient to demonstrate survivability through vibration).

The decision steps of the TIMA process, where desirable funding levels are established, requirements discarded if need be, and PACTs selected, will be adjusted as follows: The TIMA process' discarding of requirements will obviously be driven by the needs and flexibility of the flight project application(s) under consideration. The TIMA process' attribution of costs to PACTs will require some refinement. Separate pools of funding have different responsibilities: up to the point where a flight project commits to a new technology, R&D pools of funds will typically pay for that technology's advancement, including some qualification. Once sufficient maturity has been demonstrated, and a flight project commits to a new technology, then that flight project's pool of funds will cover its continued development (if any) and qualification for the specific needs of that flight project. Finally, the TIMA process' selection of PACTs will need to take into account the potential savings to be had by a careful ordering of PACTs vis-à-vis the qualification needs. We will discuss this further in a later section.

Physics of Failure

Most hardware is developed because it either improves the state of the art or it provides the satellite operator with a new capability. Since the performance is the primary motivator for the technology development effort, little to no investments are made in optimizing or assessing the manufacturability and reliability aspects of the new product.

Addressing the reliability and manufacturability at the end of the hardware development process carries the risk factors that, for example, the design approach or the materials used are ill suited for the space environment, expensive to implement, or incompatible with the spacecraft operational requirements not related to parametric performance of the new technology. Obviously, any significant change at the end of the development cycle to accommodate technology infusion is expensive and results in significant delays.

Instead, designing the technology with reliability and manufacturability in mind can significantly improve the chance of technology insertion at a reasonable cost and schedule. For this reason, we have chosen TRL 4 as the latest starting point for the infusion process. We have as a goal to identify the root cause, or physics, of the failure to provide the technology developer with the insight to mitigate the potential failure mode.

Identification of Critical Test

The evaluation and certification of flight hardware requires that each component within a subsystem is separately evaluated against rigorous institutional standards and that the screening, quality control, assembly, handling, and pedigree of all parts meet the institutional flight practices. The idea behind this approach is that the entire subsystem is only as reliable as the weakest part in the assembly. JPL has an exemplary reliability record using these reliability standards.

On the other hand, an experienced designer will select or build connectors, printed circuit boards, part packages, or housings that are likely to withstand most if not all environmental conditions. If a final screen or test reveals a manufacturing defect or design flaw, a mitigation approach is typically easily identified and relatively inexpensive to implement. The Fast Technology Infusion effort is concentrating on technology developments that lead to products with potential failure modes where no failures prevention or mitigation experience exists or where not all possible failure modes can be anticipated. This uncertainty, typically referred to as the “unknown risk of unknown failure modes”, adds a significant risk to both schedule and cost.

A typical example is the in-house developed SBC board. An experienced designer will be well versed in the temperature, temperature cycling, vibro-acoustic design, and other miscellaneous mitigation schemes needed to space qualify a typical board. Furthermore, the total ionization dose (TID) requirement of many NASA mission is small enough and the radiation specialist have enough experience with similar compute boards to project with high confidence the TID performance of the board.

However, the system level mitigation of Single Event (radiation) Effects (SEE) SBC board employs a new Error Detection And Correction (EDAC) voting scheme for evaluating the output of the PPC 750 processors embedded on board the Xilinx FPGA. This FPGA is the computational performance backbone of the board and this EAC approach adds significant risk to the project as the reliability and impact on performance is not fully understood. A part level analysis of the overall radiation susceptibility of this entire subsystem is not always possible as the SEE performance of each part is typically not known and radiation tests of all the parts is cost and schedule prohibitive. Instead, the team opted to irradiate the entire Xilinx FPGA as it is executing mission relevant software.

This approach is not new for the radiation community, however its use to screen parts for future space use and validate a new EDAC approach during mission relevant operation is untested.

Test Criticality Ordering

Appropriate ordering of the critical tests will help achieve cost and time savings in the qualification of technologies. Those tests with the greatest propensity to lead to significant technology revisions should be done first. This would avoid the need to repeat earlier tests whose results would be invalidated by a technology revision. In order to accommodate this, the cost/risk model that underpins the TIMA process will require some modest elaboration to represent the need for, and costs of, retesting/requalification.

Technology revision following a failed test may not be the only option. If testing reveals that a technology is capable of satisfying *some* of the requirements (and/or satisfying requirements in *some* of the possible ranges of operation), an alternate option would be to plan to use the technology as-is, but in a narrowed range of applications/operations. Again, we may need to adjust the TIMA process’ cost/risk model to accommodate this refinement

Cost Considerations

For almost every technology, there will be many applicable qualification activities from among which to choose. Each of them will go *some* way to evaluation and certification of *some* of the aspects of the technology in question. Spending more money and time enables more of the qualification technologies to be afforded, but becomes subject to a “law of diminishing returns”. Since the total cost of all the applicable qualification steps will far exceed the resources typically available, it becomes important to establish the cost and time expenditures to enable sufficiently assured qualification.

As described in earlier sections, we will utilize the TIMA process to capture the information relating qualification activities to the failure modes they address and relating the failure modes to the requirements they threaten. The TIMA process captures this information *quantitatively* (e.g., the cost of a qualification activity and its proportional effectiveness at detecting a failure mode). This quantitative treatment allows cost-benefit calculations to be conducted. Figure 2 below shows the cost-benefit tradespace calculated from a previous TIMA study’s data.

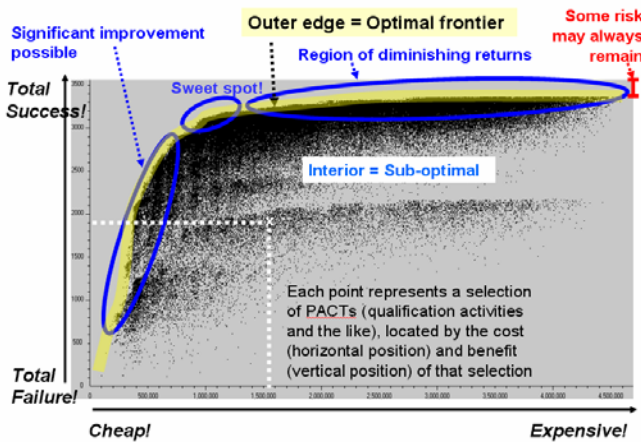


Figure 2. Cost-benefit trade space for a TIMA study.

The figure shows the cost-benefit tradespace as composed of (a sampling of) possible PACT selections. Each of the approximately 300,000 individual points in the black cloud corresponds to a distinct selection of PACTs. The quantitative model has been used to calculate the cost and benefit of each such selection, and draw a small black point corresponding to the solution: cost determines horizontal position; benefit vertical position. The upper-left frontier of the cloud is thus the optimal boundary, also referred to as the Pareto front. We have annotated the plot to indicate distinct regions of interest on the Pareto front. Points within the interior are all inferior to more optimal solutions, of course. If the budget is low, the optimal solutions fall within the region where small amounts of additional funding can lead to significant improvements (i.e., better attainment of Requirements). Conversely, if the budget is high, optimal solutions fall within the region where a law of diminishing returns operates. The ideal is to be somewhere in the sweet spot region. If the budget is too small to allow this, such a plot can motivate either a request for a budget increase, or serious consideration of descoping (reducing expectations) to be more in line with the available budget.

Cost-benefit calculations such as the above require a relatively complete set of qualitative information to have been gathered. Some of the previous TIMA studies have shown that even in the absence of fully quantified information it is still possible to make the major decisions of which qualification activities to select. The Fast Technology Infusion initiative may well proceed in a similar manner. For example, the earlier *Identification of Critical Test* section described how irradiation of the entire Xilinx FPGA was determined as the appropriate approach. The reasoning was in the spirit of the TIMA process, however without a fully quantified approach:

- radiation susceptibility was identified as a key threat;
- means to demonstrate absence from such susceptibility were identified – part level analysis, radiation tests of all the parts, or irradiation of the entire FPGA;

- the first was deemed infeasible (due to insufficient current knowledge), the second prohibitively expensive, leaving the third as the only viable selection.
- the time and effort to perform irradiation of the entire FPGA was judged to fall within the cost and timeframe of the Fast Technology Infusion’s first year effort.

In the course of the three year Fast Infusion Initiative we expect to learn more about the most efficacious approach to application of the TIMA process for the initiative’s purposes.

4. TASK SELECTION

Method for Task Selection

Following an open call and a Town Hall meeting to discuss the objectives of the Initiative, fourteen 1-page concept papers for specific technologies were submitted for review by the FTI Framework team. Proposers were reminded that the intent of the Initiative was to provide a funding opportunity to advance a technology from ~TRL-4/5 to TRL-6—that is, to provide a bridge to cross this “Valley of Death”—any successful candidate must be at least at the TRL of 4 or 5. Secondly, any candidate must be able to be rapidly infused, be a technology developed at JPL, and that have not flown in space. The selection must assure that the selected technology would not only be infused, but lead to the development and validation of a Fast Technology maturation process. As part of that process, a cost effective methodology for identifying and addressing reliability concerns must be considered. To accomplish this, the technology should be capable of being evaluated utilizing the Technology Infusion Maturity Assessment tool. This will be used to guide the maturation path and provide early guidance for technology maturation (during development). The TIMA will help develop prioritized mitigation scheme and determine what technologies need to be accelerated to support a given program and should be considered early in the selection process. The selected technologies, if successfully infused, should lead to methodologies for reducing technology maturation costs by lowering technology infusion hurdles and allowing increased leveraging of technology investments. Finally, for the hardware and software technologies addressed, it was required that technology V&V criteria could be established for each of them and that the tasks were of a nature that allowed capturing their driving requirements, significant risks, and potential mitigations.

Criteria for Task Selection

Specific evaluation criteria for the hardware proposals were:

- Evaluate based on potential customer needs and the likelihood for a return on investment.
- The expectation that if successful a viable sponsor can be identified.

- Funding must be for an instrument/technology demonstration against requirements, not for technology development.
- The key members of the original technology development team must be in place to aid in the viability demonstration
- Testbed and/or development tools must be still available
- The infuse process must be capable of being accomplished in less than 12 months and for less than \$200K per technology.

In addition to the requirements established for hardware, the following was applied to the software:

- A suitable software infusion candidate should ideally be from the last three years of internally-supported software research efforts.
- The proposal must identify key mission use(s), developers, and the operations community that it addresses.
- Validation steps should be derivable from the use scenarios
- Actual validation (testing, analysis, and evaluation) will be for ~7 mo and ~\$100K
- Time criticality factor: Need to show why it is important to fund the proposal in '07. (This is a selection consideration.)

These requirements lead to the following evaluation criteria for each proposal: Cost, Software, Maturity, Quality, Complexity, Capability, and Payoff. Each of the 14 proposal teams was given the opportunity to present their plans to the FTI review team. The proposals were then rated based on these criteria and three down-selected for final consideration. One hardware and one software proposal were ultimately found to meet the listed requirements. Finally, recommendations were made to the other proposers as to possible changes that would make their technologies suitable for consideration in subsequent years.

A Hardware Task

The objective of the hardware subtask is to verify the effectiveness of using “radiation tolerance by design” mitigation of single-event upsets in an existing JPL internal research program developed high performance single board computer (SBC). The innovative hardware qualification lies in the full system radiation exposure that will lead to the unambiguous demonstration of the SEU mitigation technique of the entire board circuitry.

Q1: Formulation of advisory board consisting of representatives of 5x representatives doing organizations (3401, 345) and potential customers: Address upgradeability issues with regard to transition from Virtex II Pro to Virtex IV and Parts List issues from point of view of radiation acceptability and package reliability.

Perform “system level” radiation evaluation of the SEU mitigation scheme by subjecting the board to functional testing while critical component(s) are irradiated with a high-energy proton beam.

Q2: Upgrade/re-fabricate test board to address issues brought out issues in parts list assessments and radiation tests. Perform functional test of SBC with radiation characterized components.

Q3: Re-perform “system level” radiation evaluation based on lessons learned in previous test and parts assessments.

Q4: Identify and pursue customers and future instrument and microspacecraft applications.

Infusion Process Flow:

The purpose of this task within the fast infusion effort is to adapt as needed the hardware infusion flow (below) to apply to software technologies slated for infusion.

A Software Task

The software demonstration of this initiative will take a high-level state-chart description of a software system and automatically generates code to implement that system. We will demonstrate state-chart design and auto code generation for the Proximity-1 communications protocol used by the MRO and MSL Electra Telecom Subsystem. This demonstration will show we can reduce costs, increase reliability, and facilitate consistent changes to any mission’s payload flight software.

Software Deliverables: A seven-month effort.

Three months after award: Existing documentation and state charts for Proximity-1 converted into UML state-charts. Previous work with other missions has shown that these state-charts can be constructed directly from the standard software documentation (SRD, Software Requirements Document) used by programmers to manually implement the code. We will use the same process for generating state-charts for Proximity-1 (hailing and ADR) based on the existing documentation.

Four months after award: Automatically generated C code from UML state-charts. Using the Autocoder test harness, we will conduct simulations to confirm that the software conforms to the Proximity-1 standard and correctly executes

the software requirements. Static code analysis (Coverity) will be used to validate the code.

Seven months after award: MRO Flight Software demonstration and verification. We will verify the generated code using existing MRO Electra flight software tests (a total of six procedures covering 21 hailing scenarios, plus six additional procedures to cover regression tests for integration with the rest of the flight software). A high-fidelity testbed containing two MRO-style Electra radios is available for this ground demonstration.

5. NEXT STEPS

The first year of the program looks at the a single software and hardware technology, and by the end of three years, at least six in-house developed technologies will have been move up the TRL ranking. Once the program has a proven track record, the goal of the program is to become self-sustaining through funding from flight programs or from general infrastructure funding.

The next goals would be to examine technologies outside JPL. Logical areas outside JPL would be the technologies developed at the various NASA centers, universities and national laboratories. Selection could be by open call, by a review of technologies through interviews, or a review of the literature such as NASA Tech Briefs, etc.

Future years would also involve a careful review and selection of commercial-off-the-shelf (COTS) technologies. However, there are a number of inherent problems in using COTS technology in space. A review of some of these issues is given in Gerke et.al.[8].

6. CONCLUSION

In this paper we have outlined a program designed to address the difficulty of infusing technologies from the laboratory environment into spacecraft. We have outlined a program that identifies two specific technologies, one hardware and one software, and outlines a path for their infusion. This path includes an evaluation using TIMA as well as the development of an infusion framework that will form an inexpensive pathway for future technologies.

It is plausible to ask whether risk analysis as typically performed by NASA missions or programs would serve the purposes described herein. We think not. Such risk analysis assumes a given design, and is used to identify ahead of time potential problems from one or more of three factors: *cost* (whether the design will be realized within budget), *schedule* (whether the design will be realized in time), and

functionality (whether the design will, during operation, perform sufficiently well as to achieve its purpose). The particular risk analysis method is chosen to match the level of detail available at the mission's or program's phase of development – e.g., qualitative approaches tend to be followed during earlier phases and quantitative approaches (notably full-featured Probabilistic Risk Analysis, [9]) during later phases. However, the assumption of a given design, more particularly of a well-understood *purpose* of the design, does not readily match to the obstacles we see recurring in attempts at technology infusion. Our approach addresses this issue by starting from an explicit listing of the many “requirements” that the new technology might be meant to satisfy. It is an integral part of our process to explore the cost/benefit ramifications of selecting among those requirements – what will it cost to guarantee (to sufficient levels of confidence) their attainment, and what is the benefit to the program/mission of doing so? We do not see traditional risk analysis practices addressing this element of decision space, and hence our motivation to apply the TIMA process, and to emerge with reusable characterizations of needs for various classes of missions.

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BIOGRAPHIES



Andrew A. Shapiro is the Division Lead Technologist for JPL's Enterprise Engineering Division and has been working in microelectronic interconnects for twenty five years. He has worked as a member of the technical staff at Rockwell International and Hughes Aircraft, where he was responsible for the packaging of a number of phased array radars and ran their high density interconnect line. As a Principal Scientist at Newport Communications/Broadcom, where the first commercial polymer 10GHz Si packages were made, he designed and packaged 10 and 40GHz optoelectronic modules. He earned his BS in chemical engineering at U.C. Berkeley, his MS in Materials Science at UCLA and his Ph.D. in Materials Science at U.C. Irvine. He has served on several national committees including NEMI optoelectronics roadmap, ECTC optoelectronics, and IMAPS education. Dr. Shapiro is also currently Assistant Adjunct Professor in Electrical Engineering at U.C. Irvine and is performing research in environmentally friendly manufacturing of electronics and optical and high frequency packaging.



Harald Schone is the Deputy Manager for the Electronics Parts Engineering Section at JPL, responsible for the reliable insertion of EEE parts into all JPL led missions. He received his master's degree in nuclear physics from the Goethe University in Frankfurt/Germany and his Ph.D. in atomic physics from the University of Heidelberg/Germany. Before joining JPL in 2004, Harald held prior positions at the Max-Planck Institute for Nuclear Physics/ Germany, Oak Ridge National Laboratory, Kansas State University, the German National Lab for Heavy Ion Research, Sandia National Labs and the Air Force Research Laboratory Space Program. His work has ranged from star evolution and fusion energy production-related atomic physics/materials research to radiation research in semiconductor devices. In addition, Harald has functioned for many years as an advisor to the Office of the Secretary of Defense in the direction and execution of DOD's space electronics program.



David E. Brinza received his B.S in Chemistry from Illinois State University in 1977 and his Ph.D. in Physical Chemistry from the California Institute of Technology in 1983. He is a Principal System Engineer in the Reliability Section at the Jet Propulsion Laboratory and is a

senior member of the AIAA. He has over 20 years experience with flight experiment development and operations with emphasis on space environments and effects measurements and new technology demonstrations. He was responsible for development and operation of the IPS Diagnostics Subsystem flown on the Deep Space 1 mission. Currently, he is the Investigation Scientist for the Radiation Assessment Detector to be flown on the Mars Science Laboratory.



Henry B. Garrett is a Principal Scientist in the Reliability Engineering organization at JPL. His background is in space physics and he has been an active participant in numerous NASA and DoD space missions serving as both a manager (Project Scientist for the AF/NASA SCATHA mission and Deputy Program Manager for the BMDO Clementine mission to the Moon) and as researcher (author of 3 books on spacecraft environments). He is an international consultant on spacecraft charging and the interplanetary environment. He received a BA in Physics (Phi Beta Kappa, magna cum laude) in 1970 and a MS and PHD in Space Physics and Astronomy from Rice University in 1974. He subsequently spent 6 years in the US Air Force before joining the Jet Propulsion Laboratory, California Institute of Technology in 1980. He is currently the Chief Technologist, Office of Safety and Mission Success. He is a member of AIAA, AGU, and AAS and a Colonel, USAF Reserves (Ret).



Martin S. Feather is a Principal in the Software Quality Assurance group at JPL. He works on developing research ideas and maturing them into practice, with particular interests in the areas of early phase requirements engineering and risk management and of software validation (analysis, test automation, V&V techniques). He obtained his BA and MA degrees in mathematics and computer science from Cambridge University, England, and his PhD degree in artificial intelligence from the University of Edinburgh, Scotland. For further details, see <http://eis.jpl.nasa.gov/~mfeather>

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